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# Assessment of cumulative inelastic displacement demand in energy dissipation systems using the Grip ‘n’ Grab tension-only mechanism

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## ABSTRACT

A ratcheting, tension-only ‘Grip ‘n’ Grab’ (GNG) device has been developed to offer resistance to loading in tension, while offering negligible resistance to compressive motion. This system can be used in conjunction with a range of seismic energy dissipation mechanisms. The single direction engagement allows for unimpeded re-seating of rocking connections removing the need for buckling restraint. Furthermore, engagement is more rapid upon reloading as the ratcheting mechanism removes residual compressive loads, reducing the amount of elastic take-up before tensile engagement.

The use of such ratcheting mechanisms can induce a large cumulative inelastic demand on the energy dissipation mechanism, which must be considered in design. This paper develops a simple OpenSEES rocking model to assess the cumulative inelastic demand imposed on the energy dissipation mechanism across a range of ground motion inputs. A parametric study across a range of structures and GNG device configurations is undertaken. The cumulative inelastic dissipater demand is normalised to the demand imposed from a single response cycle at the maximum design amplitude, to enable easy integration into structural design. This design method proposed can be easily used to approximate the cumulative demand imposed by multiple earthquakes, to ensure that the dissipative element has sufficient capacity for an earthquake and aftershock sequence.

## 1 INTRODUCTION TO THE GNG

Large earthquakes, such as the Canterbury earthquakes of 2010 and 2011, and more recent events in Japan, Chile and Kaikoura, among many others, have caused significant disturbance to communities. The cost of the

Christchurch rebuild following the earthquakes of 2010 and 2011 has been estimated to be as high as \$40 billion NZD (English 2013). The aftermath of these events has outlined and altered the different expectations of structural engineers and the general public in terms of the expected structural response. Low damage structural technology is a large field covering much of the work towards improving building performance levels following seismic events (Buchanan et al. 2012).

A key approach in this technology is the idea of providing specific energy dissipation mechanisms to absorb earthquake energy and reduce the damage to a structure. There is a wide range of options available, and research in this area continues to expand. Energy dissipation is commonly provided for structures through the use of four broadly categorised types of damping: hysteretic or metallic dampers, friction dampers (Chanci et al. 2012), viscoelastic solid dampers and viscous fluid dampers (Symans et al. 2008).

Metallic dampers or yielding steel dissipaters remain a desirable option due to the familiarity of the behaviour of steel under loading, and their general simplicity in design. However, a key issue with some common approaches, such as with buckling restrained braces (BRBs), is the presence of residual compressive stresses after a seismic event. Such stresses limit the effectiveness of the device to allow the centring of a structure post-earthquake, and also impair their performance in subsequent loading cycles. Slender bracing that yields in tension and buckles elastically in compression partially removes these residual compressive forces. However, plastic deformation on prior cycles increases the unstressed member length and results in a dead-zone with take-up on subsequent cycles. Therefore, subsequent cycles will provide delayed engagement and reduced energy dissipation capacity.

One way to address these issues is the use of a ‘Grip ‘n’ Grab’ (GNG) device. The ratcheting, tension-only engagement mechanism is designed to be used in conjunction with a dissipater, where the energy dissipation in the GNG-dissipater system can be provided by various mechanisms such as yielding or friction. The GNG device is designed to allow a dissipater to yield in tension, absorbing seismic energy, while offering almost no resistance to compressive loading, to allow for re-centring to occur. The single direction engagement eliminates residual compressive forces and removes the need for buckling restraint. A ratcheting mechanism is used to offset any increase in the length of the dissipater element, reducing take-up as the energy dissipation method engages more rapidly on subsequent cycles, and reducing the effect of impact loading. The design and testing of two prototype GNG devices is outlined in Cook et al. (2018).

Other tension-only damper and bracing research considered hysteretic dampers (Phocas and Sophocleous 2013) and seesaw systems (Kang and Tagawa 2013). Recent research has produced newer developments, including adding self-centring capability to BRB systems (Eatherton et al. 2014), using wedge spring devices to offset anchor bolt elongation in column connections (Lei et al. 2014) and a non-buckling segmented brace system with sliding joints (Hao 2015). A further project addressing these issues is a Compression-Free Device (CFD) for energy dissipative braces using an arrangement of cams and rollers with a slim steel coupon (Thammarak et al. 2017). However, the proposed GNG device offers a novel alternative that aims to be a simple, cost-effective solution for industry. The lack of resistance to compressive loading makes this device particularly suitable for use with low damage controlled rocking type structures. This application, and in particular the cumulative inelastic demand in the dissipater, is investigated in the simulations presented in this paper.

## 2 OPENSEES MODEL AND PARAMETRIC STUDY DETAILS

### 2.1 OpenSEES flexible rocking model

A two-dimensional flexible rocking frame model was created using OpenSEES software (OpenSEES 2007) and a schematic is presented in Figure 1. The purpose of the model is to provide a computationally inexpensive, yet suitable approximation of the response of a flexible rocking frame when exposed to a range

of ground motion recordings. This model allows for the examination of the effects of the Grip ‘n’ Grab device on structure response and the capacity requirements for the device to operate correctly for the duration of an earthquake event.

The model incorporates elements to simulate the behaviour of the rocking frame, GNG-dissipater systems and post-tensioning elements, with appropriate vertical and horizontal masses. A leaning column is included to model the seismic mass of the main structure connected to the rocking frame. Elastic beam-column elements with a P-delta geometric transformation were used for the frame and leaning column elements. A truss element was used to slave the horizontal DOFs of the leaning column and frame masses. Rayleigh damping of 3% critical was applied for periods of 10% and 100% of the first mode period.

The rocking mechanism and the behaviour at the base of the frame was the focus of the model. Therefore, the form of the rocking frame itself was kept simple. A total seismic tributary mass of  $M_{trib} = 21M_{frame}$  was used, and the frame mass,  $M_{frame} = 100 \text{ tonnes}$ , was assigned to a node at two thirds of the total height of the frame. This effective height was selected to provide a simple modelling approach focussed on first mode effects. While higher mode effects could be considered, the influence of higher modes is expected to have limited influence on the base rotation and the required inelastic capacity of the GNG dissipative element. The remaining part of the tributary mass,  $M_{LC} = 20M_{frame}$ , was assigned to node 9 at the same height on the leaning column. These values were selected to give a broadly accurate estimate of the relative contributions of the rocking frame and tributary masses found in a real construction. Multiple rocking frames could be used in a given design application to reduce the loading experienced by any one rocking frame.

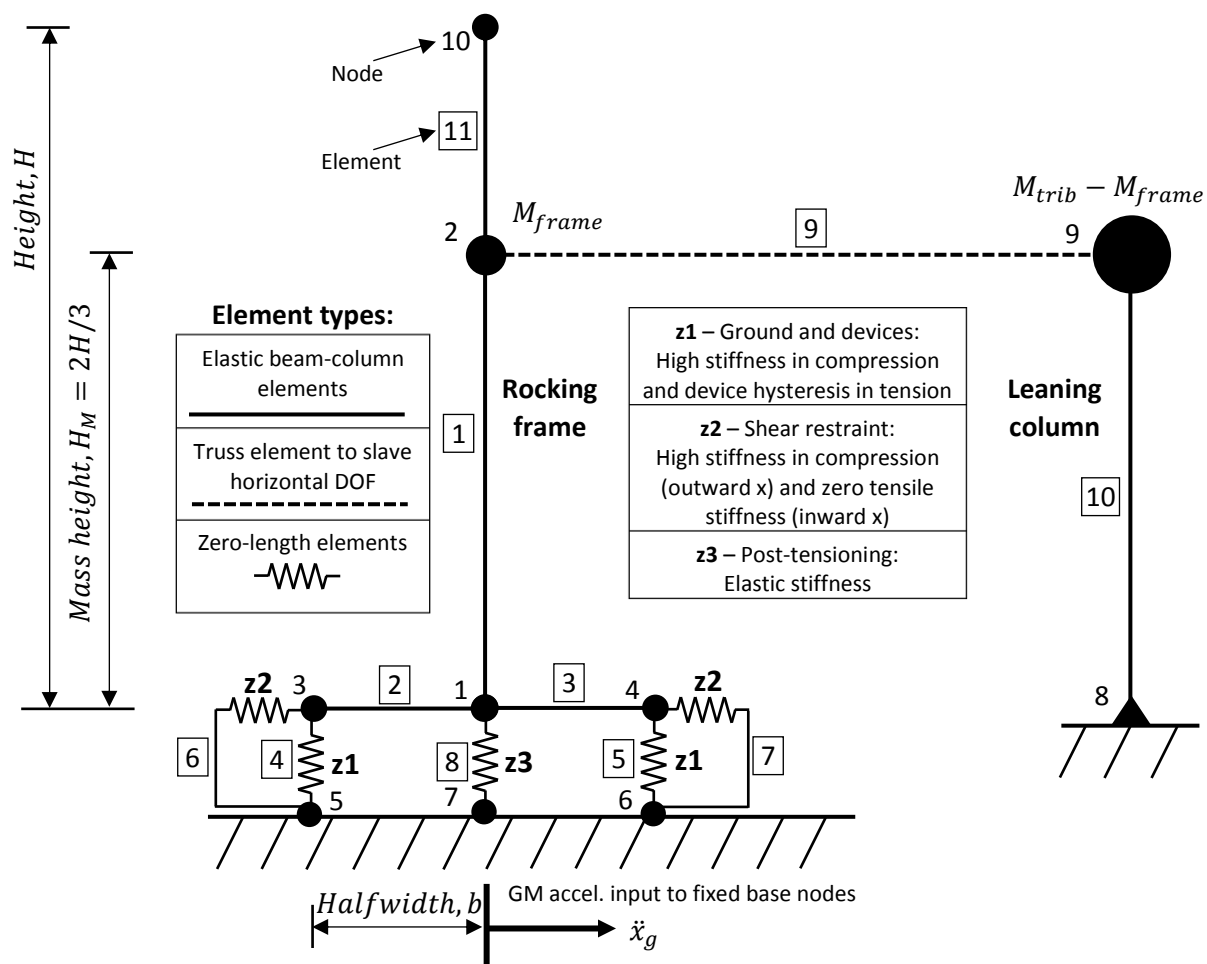


Figure 1: Flexible rocking model implemented in OpenSEES

Rocking occurs about nodes 5 and 6, shown in Figure 1, for counter-clockwise and clockwise base rotation respectively. Several zero-length elements were used to define the behaviour at the base of the frame, including horizontal supports, post-tensioning, ground interaction, and the energy dissipation devices.

Elastic-No-Tension (ENT) elements were used to model supports to transfer horizontal shear forces at the rocking edges (elements 6 and 7), and appear as **z2** in Figure 1. A high elastic stiffness was defined for displacements away from the centre of the frame (that is, negative displacements for the LHS rocking edge, and positive displacements for the RHS rocking edge), to simulate contact with the support. No stiffness was applied for displacements towards the centre of the frame (that is, positive displacements for the LHS rocking edge, and negative displacements for RHS rocking edge), to allow for base rotation following uplift. Complex sliding behaviour at the base of the rocking frame is not captured.

A custom material model algorithm was developed to capture the unique tension-only, ratcheting hysteretic behaviour of the GNG-dissipater systems. A local build of OpenSEES was compiled to incorporate the GNG material model. This material model will be available in the next release of the OpenSEES software downloadable executable file (date TBD). The GNG material model, was used in parallel with a high stiffness ENT model to simulate the response during uplift and contact with the ground respectively, at the rocking edges (elements 4 and 5), and appear as **z1** in Figure 1.

A linear post-tensioning relationship was modelled at the base of the rocking frame (element 8), with an elastic stiffness for positive displacements to simulate post-tensioning force during uplift, and appears as **z3** in Figure 1. The initial post-tensioning force was applied as an initial strain in the material constitutive model. It is assumed that post-tensioning elements will operate within the linear range of strain.

## 2.2 Parametric study

An elastic site hazard spectrum for horizontal loading was created using the guidance of the New Zealand earthquake design actions standard NZS1170.5 (SNZ 2004). Values were chosen to represent a structure located on shallow soil (site subsoil class C) in the CBD of the Wellington, New Zealand region within 2km of the nearest major fault. The structure has a design working life of 50+ years, an importance level of 3 (this is a moderately important structure that may contain people in crowds or contents of high value to the community), and is assumed to be undergoing an ULS earthquake event. The full suite of 60 SAC ground motion recordings (Sommerville et al. 1997) was scaled to the created elastic site hazard spectrum.

A parameter study was then completed using the OpenSEES model described above to assess the behaviour of the GNG devices when combined with the rocking frame system. A range of rocking frame aspect ratios and fundamental periods were considered, and each structure was simulated with 5 different GNG rack pitch sizes. The force reduction factor applied is 4, and a total of 6000 full time history analyses were completed in this main parameter study. A summary of the properties of the simulated structures is presented in Table 1.

*Table 1: Properties of simulated structures.*

Aspect ratio	Height (m)	Period (s)	GNG pitch (mm)
2	10	0.2, 0.3, 0.4	1, 2, 5, 10, 20
4	20	0.4, 0.5, 0.6, 0.7	1, 2, 5, 10, 20
6	30	0.5, 0.6, 0.7, 0.8, 0.9, 1.0	1, 2, 5, 10, 20
8	40	0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2	1, 2, 5, 10, 20

### 3 CUMULATIVE INELASTIC DEMAND

#### 3.1 Inelastic dissipater demand

The inelastic dissipater demand in the GNG devices was recorded from each individual time-history analysis completed in the parametric study. This value represents the total plastic deformation capacity required in the energy dissipation mechanism to ensure consistent operation of the GNG device for the duration of the ground motion, without fracture of the dissipater. This value is an output from the custom material model algorithm developed for the GNG device behaviour and compiled into the OpenSEES software.

Figure 2 shows the geometric mean inelastic dissipater demand in the GNG devices. The results for the left and right hand side devices are similar, but not quite the same. This level of random variation meets expectations. In most cases, a larger fundamental structure period led to greater inelastic dissipater demand. Across the range of aspect ratios and periods simulated, with a pitch of 5 mm, the geometric mean of the inelastic dissipater demand, for the device mounted on either side of the frame, ranged from 77.2 mm, for the structure with an aspect ratio of 8 and a period of 0.8 s, to 344.5 mm, for the structure with an aspect ratio of 2 and a period of 0.4 seconds.

Results where the period range assessed overlaps for structures with different aspect ratios, show a significant reduction in inelastic displacement demand with increasing aspect ratio. The flexural stiffness of the structure was determined using the fundamental period in this study, so structures with the same period experienced very similar peak roof deflections. The greater structure height associated with the larger aspect ratio means that more of the peak roof deflection is due to flexure, rather than rigid body rocking motion. The lower rigid body rotation results in smaller uplift values at the rocking edges and less displacement in the dissipaters.

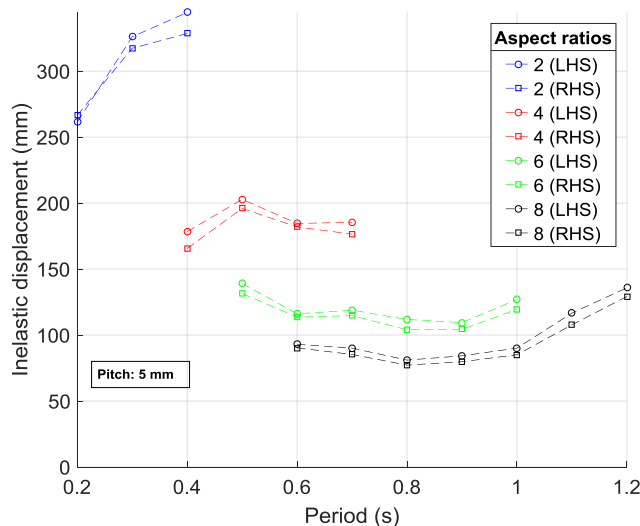


Figure 2: Geometric mean inelastic dissipater demand, for left and right side devices (pitch = 5 mm,  $R = 4$ ,  $\zeta = 3\%$ )

The effect of pitch size on the inelastic dissipater demand is shown in Figure 3. The geometric mean value from all GNG devices, both left and right sides, is presented. In most cases, a smaller pitch leads to greater inelastic demand in the dissipater, due to a reduction in free-travel from the reduced pitch size. However, it is possible for a device with a larger pitch size to experience a greater cumulative inelastic dissipater demand over the duration of a seismic event. In Figure 3, such an outcome is seen in the results for a period of 0.5 s, with the pitch size of 5 mm leading to a slightly greater geometric mean inelastic dissipater demand than the 1 mm and 2 mm pitch devices in the same analysis. However, most results show the expected trend of lower inelastic displacement resulting from the larger pitch size.

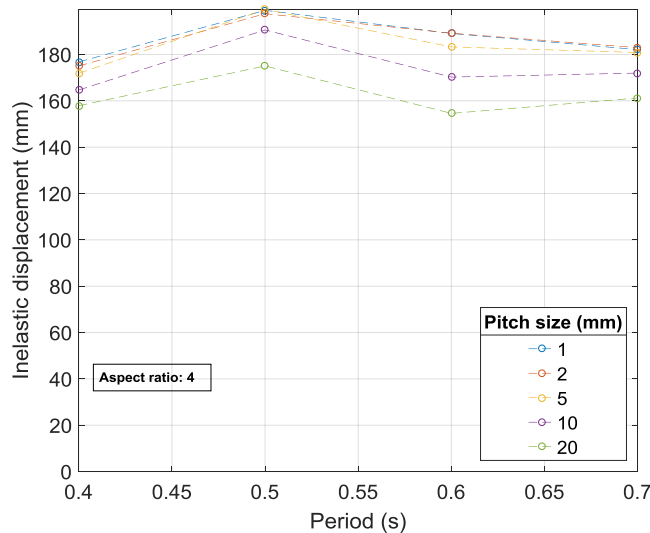


Figure 3: Geometric mean dissipater demand for all devices (both sides)  
(aspect ratio = 4,  $R = 4$ ,  $\zeta = 3\%$ )

### 3.2 Demand ratio

The ratio between the total cumulative inelastic demand in the dissipater and the peak uplift due to rocking recorded during the corresponding simulation is referred to as the ‘demand ratio’. This ratio is of particular interest in the design of a rocking system implementing the GNG device, as it provides a convenient guide for the required capacity. Figure 4 shows a comparison of the inelastic dissipater demand and peak uplift values in both the LHS and RHS devices for the 6000 analyses completed. Dashed lines are plotted indicating demand ratios of 1 and 10. Almost all of the simulated data fits within this range. Only 56 of 6000 simulations, that is 0.93%, exceed a demand ratio of 10.

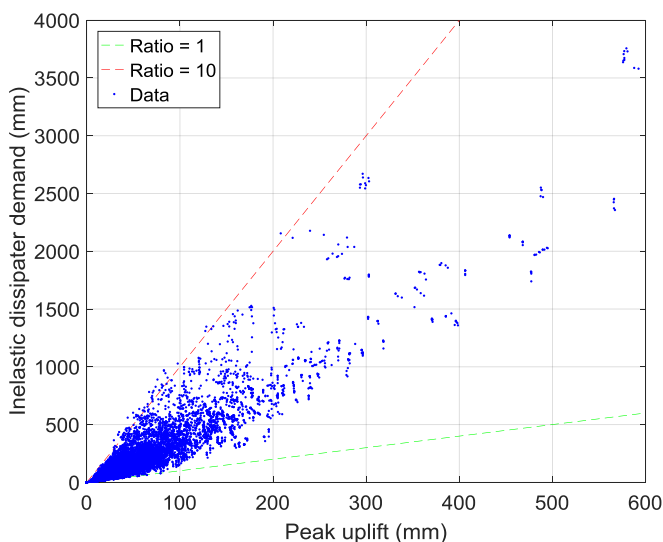


Figure 4: Inelastic dissipater demand and peak uplift, for all devices (both sides)  
( $R = 4$ ,  $\zeta = 3\%$ )

This result suggests that a design demand ratio of 10 would be suitable in most cases, without considering the dependency on GNG rack pitch size or other factors, which may allow for less conservative values in particular cases. This recommendation is based upon the simulation of ULS events, and aftershocks and



MCE motions will also need to be considered in design. Larger uplifts are expected during MCE events, but a similar demand ratio may be appropriate. A force reduction factor of 4 was used in these analyses.

## 4 CONCLUSIONS

This paper has presented selected findings of a parameter study conducted using a finite element flexible rocking model with GNG devices, developed in OpenSEES. This model allowed for the examination of the effects of the GNG device on structure response and the capacity requirements for the device to operate correctly for the duration of an earthquake event. Specific outcomes to note are:

- A series of simulated structures with varying aspect ratios, periods and GNG rack pitch sizes, using a force reduction factor of 4, were exposed to a suite of 60 ground motion records, scaled to the elastic site hazard spectrum for a Wellington based ULS event, in a parameter study consisting of 6000 individual time-history analyses.
- Geometric means of the inelastic demand in the dissipater were less than 10 times the peak base uplift from the time-history results in over 99% of the analyses.
- It is tentatively suggested that peak uplift values are multiplied by a factor of 10 to find a suitable inelastic dissipater capacity for field deployment of the GNG system with a rocking frame when subjected to ULS conditions.
- Additional considerations should be given to an MCE event and the associated inelastic demand, as well as other force reduction factors.
- Maximum cumulative demand can alternatively be normalised to code-based uplift values, which is the subject of ongoing research.

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